

## **Methods of Attenuation Correction for Dual-Wavelength and Dual-Polarization Weather Radar Data**

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In writing the integral equations for the median mass diameter and number concentration, or comparable parameters of the raindrop size distribution, it is apparent that the forms of the equations for dual-polarization and dual-wavelength radar data are identical when attenuation effects are included. The differential backscattering and extinction coefficients appear in both sets of equations: for the dual-polarization equations, the differences are taken with respect to polarization at a fixed frequency while for the dual-wavelength equations, the differences are taken with respect to frequency at a fixed polarization.

An alternative to the integral equation formulation is that based on the k-Z (attenuation coefficient- radar reflectivity factor) parameterization. This technique was originally developed for attenuating single-wavelength radars, a variation of which has been applied to the TRMM Precipitation Radar data (PR). Extensions of this method have also been applied to dual-polarization data. In fact, it is not difficult to show that nearly identical equations are applicable as well to dual-wavelength radar data. In this case, the equations for median mass diameter and number concentration take the form of coupled, but non-integral equations. Differences between this and the integral equation formulation are a consequence of the different ways in which attenuation correction is performed under the two formulations.

For both techniques, the equations can be solved either forward from the radar outward or backward from the final range gate toward the radar. Although the forward-going solutions tend to be unstable as the attenuation out to the range of interest becomes 'large' in some sense, an independent estimate of path attenuation is not required. This is analogous to the case of an attenuating single-wavelength radar where the forward solution to the Hitschfeld-Bordan equation becomes unstable as the attenuation increases. To circumvent this problem, the equations can be expressed in the form of a final-value problem so that the recursion begins at the far range gate and proceeds inward towards the radar.

Solving the problem in this way traditionally requires estimates of path attenuation to the final gate: in the case of orthogonal linear polarizations, the attenuations at horizontal and vertical polarizations (same frequency) are required while in the dual-wavelength case, attenuations at the two frequencies (same polarization) are required. For the dual polarization radar, it has been shown that the differential phase between horizontal and vertical polarization

over the path can be used to estimate path attenuation at the two polarizations. For the dual-wavelength radar, a single- or dual-wavelength surface reference technique can be used to estimate path attenuations for airborne and spaceborne geometries.

An objective of the paper is to make clear the relationships between the dual-polarization and dual-wavelength equations for both the integral equation and k-Z parameterization formulations, using a common notation. The key to understanding the differences between the integral and k-Z methods is the ways by which these methods account for attenuation and differential attenuation. A related objective is to study the robustness of the solutions when constraints are available and when they are not. We begin by writing the integral equations for the median mass diameter,  $D_0$ , and number concentration,  $N_t$ , that are applicable to both dual-polarization and dual-wavelength radar returns for the initial value and final value cases. This is followed by a similar development for the k-Z parameterization where it is noted that the initial value problem with the k-Z parameterization can be viewed as an extension of the Hitschfeld-Bordan equation to dual-wavelengths or dual-polarization. Simulations of the retrievals are presented for the case of an X-band dual-polarization radar with an emphasis on the backward-going solutions using path attenuation constraints. Sensitivities of the solutions to errors in path attenuation, the shape parameter of the size distribution, and calibration biases are used to show the relative advantages and disadvantages of the two formulations.

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